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## HIGHLIGHTS

- Natural gas reduces local air pollutants compared to traditional maritime fuels.
- First application of Technology Warming Potential in a marine setting.
- LNG may exhibit lower TWP compared to diesel under certain conditions and timeframes.
- Well-designed energy policy can promote better regional low-GHG LNG infrastructure.

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## ABSTRACT

This paper provides new knowledge about the life-cycle emissions of natural gas compared to traditional petroleum-based fuels in the marine sector. While natural gas will reduce local air pollutants, such as sulfur oxides and particulate matter, the implications for greenhouse gases depend on how the natural gas is extracted, processed, distributed, and used. Applying a "technology warming potential" (TWP) approach, natural gas as a marine fuel achieves climate parity within 30 years for diesel ignited engines, though could take up to 190 years to reach climate parity with conventional fuels in a spark ignited engine. Movement towards natural gas as a marine fuel continues to progress, and conditions exist in some regions to make a near-term transition to natural gas feasible. Liquefied natural gas in marine transportation is likely to be incentivized where economics favoring natural gas is coupled with air emissions public policy targets. To ensure that climate neutral conversion is achieved with the least delay, TWP results highlight the important role of energy policy for infrastructure development of up-stream pathways and onboard ship systems technology innovation.



## 1. Introduction

### 1.1. Overview

The maritime industry faces three new realities that are changing marine fuel investment choices. First, regulators, environmentalists, and health officials are concerned about pollutants near major coastal population centers. Marine vessels have historically emitted large amounts of pollutants into the atmosphere (Corbett and Fischbeck, 1997). Although vessels have

*Abbreviations:* BTU, British Thermal Unit; CAGR, compound annual growth rate; $CH_4$, methane; CI, compression ignited; $CO_2$, carbon dioxide; EC, East Coast Case; ECA, emissions control area; EMSA, European Maritime Safety Agency; EU, European Union; GHG, greenhouse gases; GIFT, Geospatial Intermodal Freight Transportation; GREET, Greenhouse Gas and Regulated Emissions and Energy Use in Transportation; GWP, Global Warming Potential; $GWP_{100}$, Global Warming Potential at 100 years; HP, Horsepower; HS, high sulfur distillate marine fuel (10,000 ppm sulfur); IEA, International Energy Agency; IMO, International Maritime Organization; Import Terminal, Facility that is licensed to accept natural gas from overseas; IPCC, Intergovernmental Panel on Climate Change; LA/LB, Port of Los Angeles and Long Beach; LCA, Life-Cycle Analysis; LNG, liquefied natural gas; LS, low sulfur distillate marine fuel (1000 ppm sulfur); MARAD, U.S. Department of Transportation Maritime Administration; MARPOL, International Convention for the Prevention of Pollution from Ships; $N_2O$, Nitrous Oxide; NA NG, North American Natural Gas; NG, Natural Gas; NNA NG, Non-North American Natural Gas; $NO_x$, Oxides of Nitrogen; OECD, Organisation for Economic Cooperation and Development; OGV, Ocean-Going Vessel; PANYNJ, Port Authority of New York and New Jersey; $PM_{10}$, Particulate Matter (with aerodynamic diameter smaller than 10 μm); Pathway, The set of processes utilized to get the fuel from the wellhead to the fueling station in the port.; S, sulfur; SI, spark ignited; $SO_x$, oxides of sulfur; TEAMS, Total Energy and Environmental Analysis for Marine Systems; TEU, twenty-foot equivalent unit; TFCA, total fuel-cycle analysis, which is a life-cycle analysis of fuel production and use; TWP, Technology Warming Potential; US, United States; USCG, U.S. Coast Guard; WC, West Coast Case

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become cleaner over time, international shipping still represents a large portion of local pollutant inventories, specifically along coastal areas, since 70% of the emissions are deposited within 400 km of land. Assessments for years 2007 through 2012 show that international shipping remains problematic and that these emissions may lead to significant health concerns in exposed populations (IMO, 2014b).

While the International Maritime Organization's (IMO) adoption of the International Convention for the Prevention of Pollution from Ships (MARPOL) addressed some pollutants in 1973, the response by the international maritime policy community has been aggressive of late. The IMO used the MARPOL framework to introduce regulations controlling specific pollution emissions. MARPOL's Annex VI, originally adopted in 1997, began an effort to reduce $SO_x$ and $NO_x$ emissions from ship smokestacks by initiating emissions standards for ships that reduce ship emissions rates by $\sim$80% for both sulfur and nitrogen emissions, globally, and greater than 90% reduction in IMO-designated emissions control areas (ECAs) along European and United States (US) coasts (IMO, 2013; IMO, 2014a; Lauer et al., 2009). These ECAs establish stricter emissions requirements for vessels operating within coastal areas, e.g., 0.10% sulfur limits for marine fuels, Tier III $NO_x$ controls for engine exhaust. Vessel operators, engine manufacturers, and technology providers responded with approaches to meet new standards, mainly through smokestack controls or fuel switching. Natural gas offers lower local pollution emissions compared to distillate fuels. For $NO_x$ emissions, current engine designs equal those of distillate fuels, and proposed improvements to engine design may reduce emissions to meet Tier III levels without aftertreatment (Wärtsilä, 2012). Research indicates that the $SO_x$ and $PM_{10}$ emissions of natural gas meet current, pending, and proposed standards for marine vessel operations and can significantly reduce local pollutants from vessel operations.

Second, price differences between natural gas and low-sulfur fuel oil since 2002 (IEA, 2012) suggest an economic advantage may favor natural gas (see Supporting material, Fig. D.1). An increasing number of newly constructed vessels are powered either by natural gas exclusively or by a combination of conventional diesel and natural gas (MarineLink, 2013; Posplech, 2013). Market-ready reciprocating internal combustion marine engines capable of natural gas and/or dual fuel operation enabled multiple shipbuilders to install these engines (Germanischer Lloyd, 2011; Rolls Royce, 2013). In addition, natural gas infrastructure is growing (Fullenbaum et al., 2013), making it more plausible to fuel ships with natural gas. These two drivers – the need to comply with ECA regulations and the competitive market for natural gas fuel – highlight a surge in interest in the use of natural gas as a marine fuel (Germanischer Lloyd, 2011; Posplech, 2013).

However, increased use of natural gas in the marine sector may negatively affect a third important factor: climate change. Complementing the IMO's concerns about local pollutants such as $SO_x$, $NO_x$, and $PM_{10}$, new research regarding greenhouse gas (GHG) emissions from vessel operations has stimulated efforts to reduce GHG emissions from international shipping. Currently, international shipping is responsible for $\sim$2–3% of total $CO_2$ emissions globally, and the IMO adopted mandatory measures to reduce GHGs in 2011 (Bazari and Longva, 2011; IMO, 2014b). Increased natural gas use in the marine sector may increase GHG emissions globally, due to the global warming potential (GWP) of natural gas (i.e., methane) in our atmosphere and the potential for methane leakage along the fuel production and delivery pathway (Brynolf et al., 2014a; Lowell et al., 2013; Meyer et al., 2011). When upstream emissions are considered, advantages from a GHG emissions perspective remain uncertain, because natural gas fuel production pathways can be relatively energy intensive compared to petroleum pathways, and methane leakage during natural gas extraction and distribution may have important GHG impacts (Æsoy et al., 2011; Arteconi et al., 2010; Bengtsson et al., 2011b, 2014; Brinkman et al., 2005; Brynolf et al., 2014b; Choi and Song, 2014; Elgowainy et al., 2009; Huo et al., 2008; Jayaram et al., 2010; Korakianitis et al., 2011; Lowell et al., 2013; Shen et al., 2012; TIAX LLC, 2007a; TIAX LLC, 2007b; Wu et al., 2006; Yazdanie et al., 2014).

Therefore, decision makers find it important to look at the life-cycle emissions generated by natural gas fuels compared to traditional marine bunkers (NREL, 2013). This paper expands on previous maritime life-cycle analyses by Winebrake et al. (2007) by looking at different marine case studies and applies a Technology Warming Potential (TWP) approach from Alvarez et al. (2012) to consider the implications of a fuel switch technology transition. This work evaluates whether a natural gas transition can achieve both local pollution reductions and GHG reductions in the marine sector.

We evaluate “well-to-wake” emissions for vessel operations using best available data reflecting recent research on leakage of natural gas during vessel operation and refueling. We compare multiple natural gas production and delivery pathways for three vessel case studies using natural gas with similar vessels using ECA-compliant distillate fuels meeting 2012 and 2015 standards (that is, 10,000 ppm sulfur [S] and 1000 ppm S, respectively). Specifically, a large Ocean-Going Vessel (OGV) is evaluated transiting a U.S. West Coast route, from Los Angeles/Long Beach (LA/LB) to Honolulu, HI; a coastwise OGV is evaluated transiting a U.S. East Coast route between the Port Authority of New York and New Jersey (PANYNJ) and Jacksonville, FL; and a tug/tow vessel is evaluated for typical service at a Norway natural gas terminal. These three cases represent typical transits by marine vessels and encompass long-haul cargo transport, short sea transport, and regional service vessel conditions encountered by vessels potentially fueled by liquefied natural gas (LNG). Analyzing diverse pathways examines a range of scenarios to determine the potential for benefit from a natural gas transition.

We compare emissions of $NO_x$, $SO_x$, and $PM_{10}$, for each of the three vessel case studies. We also quantify and compare GHG emissions (carbon dioxide [$CO_2$], methane [$CH_4$], and nitrous oxide [$N_2O$]) for each case. Control of $NO_x$, $SO_x$, and $PM_{10}$ from ships provides significant beneficial impacts on human health, acidification, and eutrophication (Hassellöv et al., 2013; Lauer et al., 2009; Winebrake et al., 2009), although policies to reduce short-lived aerosols from OGVs can slightly increase warming by reducing negative radiative forcing and enhancing tropospheric ozone at global scales (Capaldo et al., 1999; Lauer et al., 2009; Lawrence and Crutzen, 1999). Indirect forcing of aerosols is not considered in GWP or TWP calculations.

We apply traditional methods of quantifying GHG emissions that use the global warming potential (GWP) of the gases at a future point in time (typically either 20 or 100 years), and we also apply a TWP method that evaluates emissions across a technology's useful life. The TWP presents a warming potential value for technology conversion over time, which avoids the contentious debate over choosing an appropriate GWP base-year (Boucher and Reddy, 2008; Moura et al., 2013; Shine, 2009). This allows for an evaluation that recognizes the long lifetimes of vessel operations if traditional technologies were replaced (Alvarez et al., 2012).

Lastly, we qualitatively consider regionally variable drivers that may influence adoption of natural gas as a marine fuel using International Energy Agency (IEA) regional statistics (IEA, 2012). This regional assessment – in combination with the results of our emissions analysis – provides information necessary for policymakers assessing the potential impacts of energy and environmental policies aimed at improving air quality, reducing GHG emissions, and incentivizing a movement toward non-petroleum based fuel.

### 1.2. Emerging interest and markets for LNG as a marine fuel

Successful LNG penetration as an alternative fuel in marine engines depends on a suite of conditions for entry into a niche market and later diffusion across vessel fleets. Vessel design and performance, operations, and infrastructure are similar to conditions that supported a previous rationale for introducing hydrogen into the transportation system, in which hydrogen was studied as a potentially feasible bridge fuel (Farrell et al., 2003).

Policymakers and political bodies are engaged in understanding drivers enabling a natural gas transition in maritime transportation. Some important considerations for the switch to natural gas fueling, including safety, capital costs, operations and maintenance, and operator training, are being addressed by maritime oversight agencies like the U.S. Coast Guard (USCG) and European Maritime Safety Agency (EMSA), classification societies, and industry. Two regions where policy bodies are producing decision support documents and guidance for a maritime LNG transition include the U.S. and Europe, which have established environmental authorities, explicit energy policy strategies, and technologic capacity for engine design, vessel construction, and infrastructure investment. Other regions investing in LNG marine vessels include Dubai's LNG service tug as part of its "Green Economy for Sustainable Development Initiative" (Drydocks World, 2014), although fewer policy studies evaluating LNG in maritime use are available in these regions.

In the U.S., the transition is already occurring in land fleets, and is projected to expand into rail and marine fleets in the coming decade (Maring and Mintz, 2014). The U.S. Department of Transportation Maritime Administration (MARAD) and the USCG are studying the development and implementation of a regulatory approval process for LNG bunkering operations and associated technological and procedural risk management requirements at permitted facilities (Holden, 2014). The MARAD study identifies the following drivers for consideration of LNG as a vessel fuel: (i) air quality standards in the North American ECA; (ii) infrastructure development for LNG bunkering; (iii) social concerns about safety and regulatory gaps (including ways to reduce $CH_4$ leakage in downstream fueling and operation); (iv) price differences; and (v) increased demand for maritime fuel (Holden, 2014).

European studies of LNG as a shipping fuel indicate that LNG offers long-term compliance with increasingly stringent maritime emissions standards (European Parliament, 2012) and is consistent with directives to deploy alternative fuels infrastructure (European Parliament, 2014). Europe considers natural gas in transport to support broader social objectives to improve "the security of Europe's energy supply, support economic growth, strengthen the competitiveness of European industry, and reduce greenhouse gas emissions from transport" (European Commission, 2013).

A forthcoming study by the European Commission acknowledges that environmental performance goals and infrastructure are necessary conditions, but the "most critical issues for further deployment are the financing of LNG as a fuel and the pricing of LNG itself" (European Commission Maritime, 2015). A 2012 study considered two perspectives: (a) the opportunity for LNG in ships to achieve compliance with ECA standards at lower cost than other options; and (b) the expected payback period for several ship types if they were to switch to LNG relative to switching to compliant marine distillate fuels (Danish Maritime Authority, 2012). The Danish Maritime Authority considered several types of cargo transport vessel, and recognized that some ship types "will be more inclined to choose the LNG strategy" that other ship types on the basis of cost-effectiveness and payback.

## 2. Methods

### 2.1. Overview of total fuel-cycle analysis

Total fuel-cycle analysis (TFCA) is a type of life-cycle analysis modeling for fuel production and use. The approach accounts for energy use and emissions along the entire "fuel cycle," which includes the following stages (DeLuchi, 1991; Wang, 2002):

*Extraction stage* – extraction of the raw material through delivery to the refinery;

*Processing stage* – refinement of a fuel, including liquefaction in the case of natural gas, and delivery to the vessel (the extraction and processing stages together can be referred to as the "upstream" stages); and,

*Operation stage* – combustion of the fuel in the vessel itself (main propulsion and auxiliary engines can be referred to as the "downstream" stages, including the recovery and combustion of evaporating stored gas that would "boil off" in a land-side storage context).

Total emissions are calculated by summing emissions during each stage (separating out main and auxiliary engines) using the method of Winebrake et al. (2007). Many pathways exist to get fuel from source to ship (Lowell et al., 2013). Looking at the emissions from multiple pathways can help analysts evaluate those fuel production pathways that may incur the least emissions penalties.

Fuel-cycle analyses mainly aimed at economic or carbon metrics were first published in the life-cycle analysis (LCA) literature (DeLuchi, 1991; Manne et al., 1979). Total fuel-cycle analysis became a specialized and unique type of LCA as alternative fuels were considered for both air quality and carbon emissions (Schlamadinger and Marland, 1996; TIAX LLC, 2007a, 2007b), and as dedicated models focused on current and alternative pathways for transportation fuel (Wang, 2002; Winebrake et al., 2001). TFCA became more critical with emergence of Low-Carbon Fuel Standards regulation (Farrell and Sperling, 2007) and recognition of the importance of land use change and emerging extraction methods for low carbon fuels.

In a maritime context, TFCA emissions require specialized understanding of "downstream" or operational characteristics of these vessels and fuels. Marine application of TFCA, recognized as an important part of marine fuel evaluations (Adom et al., 2013), were first developed around 2005 (Corbett and Winebrake, 2008b; Winebrake et al., 2007). Some of these studies explored in particular the tradeoffs associated with a shift to clean marine fuels from both a local pollutant and GHG perspective (Bengtsson et al., 2011a; Bengtsson et al., 2014; Brynolf et al., 2014b; Corbett and Winebrake, 2008a). For example, Corbett and Winebrake (2008b) demonstrated that a switch from residual fuel to 0.1% sulfur distillate fuel could achieve ~97% reduction in sulfur emissions, but would lead to a net increase in $CO_2$ emissions of approximately 1% to 2% over the total fuel cycle. This net change in fuel-cycle $CO_2$ is a function of increased energy required at the refining stage to produce compliant distillate fuel and decreased energy during ship operation on distillate fuel compared to residual fuel. Similar types of tradeoffs are shown in Winebrake et al. (2007) which evaluated local and global emissions characteristics of marine vessels across a number of different fuel types and vessel types.

We use the Total Energy and Environmental Analysis for Marine Systems (TEAMS) model, the first extension to quantify life-cycle analysis in the marine sector based on the Greenhouse Gas and Regulated Emissions and Energy Use in Transportation (GREET) model (ANL, 2014). TEAMS evaluates downstream marine characteristics and adapts GREET's upstream components (Winebrake et al., 2006). The customizable downstream marine model in TEAMS works well with two other modeling platforms: upstream results from later versions of the GREET model (Corbett and Winebrake, 2008b; Elgowainy et al., 2009; Huo et al., 2009; Milliken et al., 2007; Wang et al., 2008; Winebrake et al., 2001, 2007; Wu et al., 2006) and geographic characterization using the Geospatial Intermodal Freight Transportation (GIFT) model (Corbett and Winebrake, 2008b). In combination, these models allow one to construct unique fuel pathways for LNG and conventional fuels, to create routes along international shipping corridors from origin ports to destination ports, and to calculate emissions of local and global air pollutants along the entire fuel production and use pathway.

We use a modeling approach that incorporates GREET 2013 for our upstream analysis with TEAMS for our downstream analysis, with GIFT measurement of input distances and case visualization to construct an analysis that integrates the best of these modeling environments. Unless discussed elsewhere, the default GREET 2013 (ANL, 2014) and TEAMS emissions factors were used for all processes (see Supporting material, Section B for supplementary detail), except in the Norway case, where the average Norway electricity mix (IEA, 2015) and EU refining efficiencies (Han et al., 2015) were used.

GHGs are often reported jointly by applying GWP ratios to emitted GHG species, as is done here using the current IPCC (AR5) values (Myhre et al., 2013). This can be problematic, however, because GWP values for different GHG gases vary over time (Boucher and Reddy, 2008; Shine et al., 2005). Therefore the time period chosen can influence the reported climate impact. To gain a more complete picture, Alvarez et al. (2012) developed the concept of the "technology warming potential" (TWP) which considers the climate impact of a technology transfer over time, avoiding the contentious debate over time period choice. The TWP is a ratio of the new technology (here LNG vessels) to the existing (both high- and low-sulfur diesel vessels), with TWP=1 indicating climate neutrality, and incorporates both $CO_2$ and $CH_4$ according to Alvarez et al. (2012). $N_2O$ is not included in the formula because it is a much smaller component than the other two and the intention by Alvarez et al. was to highlight the impact of $CH_4$ (Personal communication with Ramón A. Alvarez, 16 July 2015). This paper applies the "fleet conversion TWP," because permanent fuel switchover is the most likely maritime LNG scenario after investment in infrastructure to change technologies. The full equations for the two are shown in Eq. (A.1) of Supporting material, Section A. A "fleet conversion" does not imply that every single vessel will be switched, but rather that replacement vessels for those already switched to LNG will not revert back to diesel. While this concept has been used for on-road vehicles (Alvarez et al., 2012; Camuzeaux et al., 2015), to our knowledge this work is the first to extend TWP analysis to maritime vessels.

### 2.2. Construction of fuel pathways

A "fuel pathway" represents the series of processes that are necessary for fuel production and use. Various steps in the process are shown generically in Fig. 1. Multiple fuel pathways exist for a given fuel. We explore 28 possible fuel pathways for natural gas fuels. The variables considered are contained in Table 1. Variables that change include fuel type and source; location of liquefaction for LNG; transportation mode for the processed fuel; and storage alternatives. Not every fuel pathway applies to all locations (i.e., ports) and details of which pathways apply to each port are shown in supporting material, Table A.1. A range of representative pathways are selected, including current and future "best case" scenarios that minimize transportation distances. Further explanation can be found in a MARAD report on natural gas pathways (Corbett et al., 2014).

Unlike the natural gas market, where different upstream pathways are being examined for economic and environmental

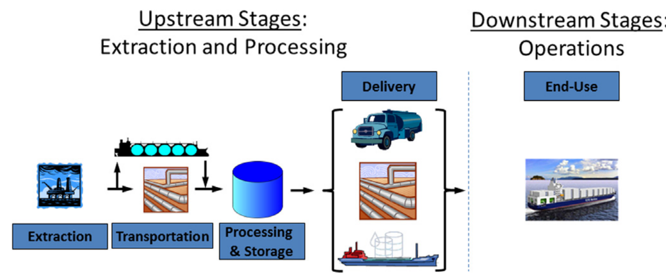



**Fig. 1.** Generic pathways showing total fuel-cycle processes, including extraction and processing of feedstocks to the ultimate end-use in a marine vessel.

criteria, the distillate fuel market is mature, with established upstream pathways. Therefore, we use default GREET 2013 pathways for all upstream distillate processes for ECA-compliant distillate fuels that we compare with natural gas pathways.

### 2.3. Case descriptions

We define a "case" as the collection of applicable fuel pathways to a given vessel route. Each pathway represents a defined upstream pathway combination providing fuel to a particular vessel operating out of a given port, along a fixed route. For upstream emissions, various pathways for transporting the natural gas to the port were examined. Pathways are differentiated by numbers. For downstream emissions, a vessel was modeled that typically transits that route (see Section 2.4.1). This is shown in some detail for the West Coast case; further details and full details for the other two cases can be found in Supporting material, Section A. The details of each pathway are shown in supporting material, Table A.1 a and b.

#### 2.3.1. West Coast Case

The West Coast Case pathways examine the emissions from using an LNG powered vessel to transport goods from the Port of LA/LB to Honolulu, HI. The case includes evaluation of all relevant fuel pathways, based on the fueling situation in and around LA/LB. The LNG is either imported from a non-North American natural gas (NNA NG) source as LNG via tanker, or processed from North American natural gas (NA NG). For the latter, we assume that NA NG is extracted from an existing well and delivered via pipeline to a liquefaction facility. We quantify liquefaction an existing facility, and at a facility closer to the port at the nearest terminus of existing large volume pipelines to represent the possibility of future

**Table 1**
Pathway variables and potential values of each variable.

| Pathway variable | Potential values |
|---|---|
| Location of Natural Gas Drilling | • Drilled on continent (Continental NG)<br>• Drilled off continent and pipelined or tankered to continent (Non-Continental NG) |
| Continental | • Conventional (North America and Europe)<br>• Shale (North America only) |
| Non-Continental | • Transported directly from import terminal<br>• Regasified and injected into the domestic pipeline where it is then treated as domestic pipeline gas |
| Liquefaction and Compression | • On-site liquefaction facility<br>• Closest existing facility<br>• Closest potential facility |
| Transportation | • North America: barge or truck<br>• Europe: liquefaction facility is on-site; no further transportation necessary |
| Storage | • Minimum: 5 days<br>• Maximum: 30 days, before pressure increase exceeds quality and safety thresholds |

construction. A truck or barge delivers LNG from the liquefaction facility to the port.

For NNA NG, we assume imported LNG will come to the Port of LA/LB from Qatar to the nearest import terminal in Ensenada, Baja California, Mexico, then transported by truck, barge, or pipeline (after re-gasification) to the port. For NA NG, we assume the natural gas is extracted from the closest natural gas field to this port (Elk Hills, CA), and is pipelined to the closest existing liquefaction facility (north of the port in Boron, CA). There is a pipeline terminus located closer to the port in Long Beach, CA. Fig. 2 shows the facilities on the map, and Supporting material, Section A, Table A.1 reports the distances for each of the transportation segments of this fuel pathway.

### 2.3.2. East Coast Case

The East Coast pathways examine the emissions from using an LNG powered vessel to transport goods from the PANYNJ to Jacksonville, FL. The case includes evaluation of specific, relevant fuel pathways for the fueling situations in and around PANYNJ and Jacksonville. Vessel inputs are shown in Table 2 while further details about the inputs for the port can be found in Supporting material, Section A.

### 2.3.3. Norway Case: service vessel tugboat

The Norway pathways consider emissions from using an LNG powered tugboat, the Borgøy, which operates at the Kårstø gas terminal in Kårstø, Norway. It remains in the port, assisting vessels transporting natural gas products, with service times of five days in between fueling. Further details about the vessel are shown in Table 2, with inputs summarized in Supporting material, Section A.

## 2.4. Determination of model inputs

### 2.4.1. Vessel characteristics

We match vessels to the routes described above corresponding to typical commercial service based on port databases of vessel calls. Downstream vessel characteristics for the large container vessel (West Coast Case), the smaller shortsea container vessel (East Coast Case), and the service tug vessel (Norway Case) are evaluated with the TEAMS model. We consider this study a "well-to-wake" similar to the well-to-wheels approaches using GREET and other methods for onroad vehicles. A "well-to-wake" study focuses on the contribution of different fuels and engine technologies that deliver vessel propulsion power. Potential different hull configurations that would be expected for a ship designed for LNG storage vs. other liquid fuel storage would involve naval architecture design calculations that are considered to produce the same performance, e.g., same vessel power output, same vessel speed for engine load, same distance traveled for the route, and same cargo payload (containership) or work done (tug).

For all cases, we consider state-of-the-art engines that represent engines likely to be selected for large-scale marine deployment of natural gas when considering engine efficiency and control of $CH_4$ emissions, sometimes called "methane slip." We modeled single-engine vessel configurations for larger horsepower (HP) vessels, which operate using a Diesel Cycle. While large ships can use dual Otto-cycle engines in combination, single engine configurations are more typical. In the Norway case, partly because mid-range engine manufacturer designs are both Diesel and Otto Cycle, we model both engine profiles. Modeling the Otto Cycle engine produces higher $CH_4$ combustion emissions because of greater methane slip rates, and the OGV life-cycle $CH_4$ emissions increase compared with the Diesel Cycle engine.

Engine manufacturers are providing gas and dual-fueled engines that report thermal efficiency from ~40% to ~50% for newer-model engines on both Otto and Diesel Cycles (Rolls-Royce, 2014; Wärtsilä, 2014). This represents a state-of-achievement engine efficiency for new engines likely to be used in modernization and repowering associated with a large-scale increase in marine applications of LNG. Our case design compares new natural gas engines with new diesel engines rather than comparing current older diesel technology to more fairly evaluate life-cycle GHGs resulting from technology transition in a fleet modernization context. For this work, we select the middle of the range of reported efficiencies (45%) for new and emerging LNG marine engines as well as current diesel engines. This is consistent with earlier studies (Brynolf et al., 2014b) that concluded using the same efficiency was the most realistic assumption.


**Fig. 2.** Depiction of various fuel pathways for the West Coast Case showing transportation modes along the pathway network.

**Table 2**
Vessel characteristics for each case study.

| | West Coast Case | East Coast Case | Norway Case |
|---|---|---|---|
| **Vessel characteristic** | **Long ocean voyage** | **Shortsea voyage** | **Service vessel harbor craft** |
| Vessel type | Container | Container | Tug |
| Engine type | Compression-ignited | Compression-ignited | Both spark- and compression-ignited |
| Average DWT | 32,000 | 37,300 | |
| Rated power (kW) | 23,860 | 22,000 | 3400 |
| Distance (miles) | 2,230 | 828 | 58 (per day for 5 days) |
| Rated speed (knots) | 22 | 22 | 13.5 |
| Time for one-way trip (hours) | 130 | 40 | 120 (Hours between refueling) |
| Engine efficiency[a] (%) | 45 | 45 | 45 |

Time spent in each operating stage as a percentage of total trip time (%)

| Mode type | Typical load | WC Time in mode | EC Time in mode | Mode type | Typical load | Norway time in mode[b] |
|---|---|---|---|---|---|---|
| Idle | 2 | 1.25 | 1.25 | Idle | 0 | 0.00 |
| Maneuvering | 8 | 1.75 | 1.75 | Mode 1 | 5 | 20.00 |
| Precautionary | 12 | 5.00 | 5.00 | Mode 2 | 30 | 40.00 |
| Slow Cruise | 50 | 85.00 | 7.00 | Mode 3 | 50 | 36.00 |
| Full Cruise | 95 | 7.00 | 85.00 | Mode 4 | 65 | 4.00 |

[a] Engine efficiency from Bergen C-gas engine specification sheet; higher engine efficiency reported in 2003 presentation by Sindre Håberg (2003); our study uses 45% for all engines.
[b] Loads and times per those reported in (Kunz and Gorse, 2013).

We apply engine emissions rates representing downstream exhaust pollutant profiles for both natural gas and diesel fuels in marine engines, shown in Supporting material, Section B, Table B.1 (Corbett et al., 2014). For OGVs using low-speed diesel engines operating on natural gas, prior applications of the TEAMS model used emissions rates for compression-ignited natural gas engines or petroleum fueled diesel engines. In this work we apply results of recent research suggesting that the emissions factors for spark-ignited (Otto-cycle) 4-stroke combustion engines are different than compression-ignition (Diesel-cycle) engines for some pollutants (Kunz and Gorse, 2013). Otto-cycle engines operate at medium speeds, which is more typical of smaller vessels, such as in the Norway tug case.

Table 2 shows downstream characteristics used for a typical vessel on each route, based on values obtained from the Lloyd's database for container vessels. For most variables default TEAMS values were used; however, because “slow steaming” is becoming the transiting method of choice on long routes in order to save fuel (Jorgensen, 2011; Meyer et al., 2012), the West Coast Case operating mode inputs defined the majority of the voyage time to be slow steaming. For the Norway case, the tug engages in different engine modes than a cargo transport vessel (Kunz and Gorse, 2013), so inputs were matched to a typical tug duty cycle.

### 2.4.2. Upstream emissions factors

Inputs used for upstream processes affect final TFCA results. For instance, Choi and Song (2014) found that in Korea the emissions were higher than in the U.S., because Korea imports almost all of its natural gas, which takes more energy than simply running it through a pipeline as in the U.S. Arteconi et al. (2010) found that changes in upstream pathways can be the difference between GHG savings or parity as compared to diesel fuel. Moreover, GREET 2013 updated emissions factors for various upstream $CH_4$ processes (Burnham et al., 2013). These factors in GREET 2013 have been supported by research findings on leakage rates (Alvarez et al., 2012; Howarth et al., 2011) though some more recent research suggests these values might underestimate actual leakage (Brandt et al., 2014).

For this reason, we perform a sensitivity analysis on the GREET 2013 default values for upstream $CH_4$ emissions from leakage, venting, and flaring during various stages for the pathway with the largest methane emissions to evaluate potential effect of this uncertainty on the overall results (see Section 3.3). Natural gas leakage assumptions for transmission and distribution stages can be critical to the analysis of overall GHG emissions, especially across longer distances. Our case studies consider pathways with varying distances to quantify how much this may matter, as discussed in Corbett et al. (2014).

### 2.5. Identification of energy policy drivers for LNG conversion

As a second analytical component, we qualitatively evaluate five dimensions of market development for energy conversion in marine transportation. These can be thought of as top-level drivers motivating both public policy and business decisions with regard to the choice and timing of LNG introduction into marine transportation, including:

- Environmental – Stricter emissions control regulation, especially addressing regional shipping, favors cleaner fuels like LNG in marine transportation.
- Social – More active alternative energy and climate policy activity favors fuels that meet national and international GHG commitments.
- Infrastructure/Technology – Developed fuel infrastructure across the fuel cycle, and vessel/engine technology design capacity favors fuel transition to LNG in marine transportation.
- Economic Price – Regional long-term fuel prices lower than world average favor a fuel transition.
- Maritime Demand – Long-run price competitiveness, port growth, and regional price advantages for alternative fuels favors fuel transition investment strategies.

This qualitative analysis offers an energy policy, economic, and environmental context within which the important LCA results can be better understood. We evaluate these drivers for each IEA region to determine whether regional contexts may favor or inhibit investment in marine sector natural gas infrastructure. We provide overall results for each region based on regulations, policies, and data for price and maritime demand, recognizing that regional characteristics may mask sub-region diversity.

We attempt to identify regional conditions that favor LNG development based on the drivers above, including: (a) environmental regulation to reduce criteria air pollutants; (b) social policy commitments to limit GHGs with alternative energy strategies; (c) favorable fuel pricing compared with world average LNG prices; (d) LNG consumption history (particularly in the transport sector); and (e) major port growth in twenty-foot equivalent unit (TEU) volume or cargo tonnage (AAPA, 2013). We consider LNG pricing trends, LNG consumption history, and potential maritime LNG demand growth (IEA, 2012). Our goal is a high-level regional assessment identifying current or emerging conditions that might favor maritime transition to LNG. This is related to the TFCA because LNG infrastructure can affect upstream pathway emissions, and LNG fleet technology investment can modify downstream emissions.

## 3. Results

### 3.1. Total fuel-cycle results for emissions

Emissions were calculated for the stages of each fuel pathway, and results represent emissions for a given "trip." For example, "$NO_x$" represents the amount of $NO_x$ emitted while obtaining, processing, transporting, and consuming the fuel needed to transport the ship across the specified distance for each case. The feedstock stage and fuel processing stage describe emissions occurring *upstream* (well-to-pump); the main and auxiliary engine operations describe emissions occurring *downstream* (pump-to-wake). GHG calculations treat each trip as a single, one-time, pulse of emissions. Table 3 shows results for each pathway in the West Coast Case, while Table 4 shows results for the East Coast Case and Table 5 shows results for the Norway case. Details for each pathway are described in Supporting material, Table A.1.

Dominant pathway stages for total fuel-cycle emissions varied by the compound emitted. For both $CO_2$ and $N_2O$ most of the emissions come from the downstream stages. However, for $CH_4$ the differences in the upstream processes significantly contributed to emissions. For example, natural gas obtained from shale has higher $CH_4$ emissions than that from conventional gas, while shorter storage times decrease emissions. The amount of $CH_4$ released during downstream combustion (sometimes termed methane slip) in the engine can be greater than (or similar to) the amount of leakage that occurs during upstream processing and transport. Further details can be found in Corbett et al. (2014).

### 3.2. Air quality pollutant comparisons with traditional marine fuels

We compare two criteria pollutants to illustrate that LNG reduces emissions compared to traditional marine fuels. For each case, and in the subsequent graphs, values were normalized to the average of the low sulfur diesel pathways, as that is the fuel type meeting current regulations (as of 2015). Fig. 3 shows how particulate matter and sulfur oxide emissions compare for the three cases. Switching to natural gas (NG in tables) provides a decided benefit for both, especially compared to the high sulfur pathways. As shown in Tables 3–5, $NO_x$ was unchanged for all pathways, being reduced only when the Otto-Cycle engine was used. The graph for $NO_x$ is shown in Supporting material, Section C.

Natural gas fuel in marine transportation can produce significantly less $PM_{10}$ and $SO_x$ than the diesel fuel pathways, but produces similar $NO_x$ emissions with similar combustion temperatures and cylinder conditions. Pollution reductions for a given trip (as modeled here) will continue to accrue with a technology conversion. In other words, a transition to natural gas will likely meet or exceed all current and projected regional air emissions standards for $PM_{10}$ and $SO_x$ from marine engines.

**Table 3**
West Coast Case results for total fuel-cycle emissions (in kg/trip) of pollutants included in this study for travel from the Port of LA/LB to Honolulu, HI.

| Pathway code | Kilograms emitted per trip | | | | | | |
|---|---|---|---|---|---|---|---|
| | $NO_x$ (000) | $PM_{10}$ | $SO_x$ | $CO_2$ (000) | $CH_4$ (000) | $N_2O$ | GHGs (000) |
| LA1 | 32 | 120 | 326 | 936 | 4.8 | 29 | 1089 |
| LA2 | 32 | 116 | 324 | 923 | 4.9 | 29 | 1078 |
| LA3 | 33 | 117 | 326 | 935 | 5.4 | 35 | 1106 |
| LA4 | 32 | 82 | 210 | 900 | 5.0 | 31 | 1057 |
| LA5 | 32 | 82 | 206 | 898 | 3.6 | 31 | 1014 |
| LA10 | 32 | 81 | 209 | 895 | 5.0 | 31 | 1051 |
| LA11 | 32 | 81 | 204 | 894 | 3.6 | 31 | 1008 |
| LA12 | 32 | 82 | 210 | 899 | 5.7 | 31 | 1077 |
| LA13 | 32 | 82 | 205 | 897 | 4.3 | 31 | 1034 |
| LA18 | 32 | 81 | 208 | 894 | 5.6 | 31 | 1071 |
| LA19 | 32 | 81 | 204 | 892 | 4.2 | 31 | 1028 |
| **WC Average** | **32** | **91** | **239** | **906** | **4.7** | **31** | **1056** |
| WC_LS | 32 | 993 | 900 | 1195 | 1.4 | 29 | 1245 |
| WC_HS | 32 | 993 | 3370 | 1276 | 1.4 | 29 | 1326 |

Note: Pathway Code refers to the port of origin ("LA" being the Port of LA/LB) and the fuel pathway for refueling (indicated by the number as referenced in Supporting material, Section A, Table A.1).
Note: GHGs represent the $GWP_{100}$ weighted combination of $CH_4$, $CO_2$, and $N_2O$; GREET and TEAMS multipliers (1 g $CO_2$ = 1 g $CO_2$e; 1 g $CH_4$ = 30 g $CO_2$e; and 1 g $N_2O$ = 265 g $CO_2$e) are consistent with current (AR5) IPCC multipliers for 100-year equivalent per-mass warming potential compared to $CO_2$.

**Table 4**
East Coast Case results for total fuel-cycle emissions (in kg/trip) of pollutants included in this study for travel between the Port Authority of New York/New Jersey (PANYNJ) and the Port of Jacksonville, FL.

| Pathway code | Kilograms emitted per trip | | | | | | |
|---|---|---|---|---|---|---|---|
| | $NO_x$ (000) | $PM_{10}$ | $SO_x$ | $CO_2$ (000) | $CH_4$ (000) | $N_2O$ | GHGs (000) |
| NY1 | 15 | 38 | 115 | 441 | 1.9 | 14 | 501 |
| NY2 | 15 | 35 | 115 | 432 | 1.9 | 14 | 495 |
| NY3 | 15 | 35 | 113 | 435 | 2.2 | 17 | 504 |
| NY6 | 15 | 29 | 95 | 428 | 2.5 | 16 | 507 |
| NY7 | 15 | 29 | 93 | 428 | 1.8 | 16 | 486 |
| NY14 | 15 | 29 | 95 | 428 | 2.8 | 16 | 517 |
| NY15 | 15 | 29 | 93 | 427 | 2.2 | 16 | 496 |
| J1 | 15 | 37 | 115 | 436 | 1.9 | 14 | 496 |
| J2 | 15 | 35 | 114 | 431 | 1.9 | 14 | 492 |
| J3 | 15 | 38 | 118 | 445 | 2.1 | 16 | 511 |
| J4 | 15 | 33 | 101 | 448 | 2.9 | 20 | 539 |
| J5 | 15 | 33 | 99 | 446 | 2.2 | 20 | 517 |
| J8 | 15 | 31 | 101 | 445 | 3.1 | 22 | 544 |
| J9 | 15 | 31 | 99 | 443 | 2.4 | 22 | 522 |
| J12 | 15 | 33 | 101 | 447 | 3.2 | 20 | 549 |
| J13 | 15 | 32 | 99 | 446 | 2.6 | 20 | 527 |
| J16 | 15 | 31 | 101 | 444 | 3.5 | 22 | 554 |
| J17 | 15 | 31 | 98 | 443 | 2.8 | 22 | 532 |
| **EC average** | **15** | **33** | **104** | **438** | **2.4** | **18** | **516** |
| EC_LS | 15 | 475 | 434 | 574 | 0.7 | 14 | 598 |
| EC_HS | 15 | 475 | 1643 | 613 | 0.7 | 14 | 638 |

Note: Pathway Code refers to the port of origin ("NY" being the PANYNJ; "J" for Jacksonville) and the fuel pathway for refueling (indicated by the number as referenced in Supporting material, Section A, Table A.1)
Note: GHGs represent the $GWP_{100}$ weighted combination of $CH_4$, $CO_2$, and $N_2O$; GREET and TEAMS multipliers (1 g $CO_2$ = 1 g $CO_2$e; 1 g $CH_4$ = 30 g $CO_2$e; and 1 g $N_2O$ = 265 g $CO_2$e) are consistent with current (AR5) IPCC multipliers for 100-year equivalent per-mass warming potential compared to $CO_2$.

### 3.3. GHG comparisons with traditional marine fuels

Most GHG calculations define the GWP as a pulse, assuming that emissions occur once and then slowly decay from the atmosphere; the GWP ratio is evaluated for one particular point in time

**Table 5**
Service vessel Case results for total fuel-cycle emissions (in kg/service range) of pollutants included in this study for for routine operations elecin the Kårstø gas terminal.

| Pathway code | Kilograms emitted per 5-day service range | | | | | | |
|---|---|---|---|---|---|---|---|
| | $NO_x$ (000) | $PM_{10}$ | $SO_x$ | $CO_2$ (000) | $CH_4$ (000) | $N_2O$ | GHGs (000) |
| Medium speed gas, Spark-ignited natural gas engine | | | | | | | |
| N_SI1 | 4.6 | 58 | 21 | 136 | 0.6 | 7 | 155 |
| N_SI2 | 4.6 | 58 | 21 | 132 | 0.4 | 4 | 146 |
| N_SI3 | 4.5 | 58 | 23 | 132 | 0.3 | 4 | 142 |
| N_SI4 | 4.5 | 58 | 23 | 132 | 0.5 | 4 | 147 |
| N_SI5 | 4.5 | 57 | 21 | 132 | 0.3 | 4 | 143 |
| N_SI6 | 4.5 | 57 | 20 | 136 | 0.6 | 7 | 155 |
| **SI average** | **4.5** | **58** | **21** | **133** | **0.5** | **5** | **149** |
| Low speed, compression-ignited natural gas engine | | | | | | | |
| N_DI1 | 2.7 | 2 | 16 | 78 | 0.7 | 6 | 160 |
| N_DI2 | 2.7 | 2 | 16 | 78 | 0.6 | 5 | 156 |
| N_DI3 | 2.6 | 3 | 17 | 74 | 0.4 | 2 | 147 |
| N_DI4 | 2.6 | 2 | 17 | 74 | 0.3 | 2 | 143 |
| N_DI5 | 2.6 | 2 | 15 | 74 | 0.5 | 3 | 148 |
| N_DI6 | 2.6 | 2 | 15 | 74 | 0.3 | 3 | 144 |
| **DI average** | **2.6** | **2** | **16** | **75** | **0.5** | **4** | **150** |
| Petroleum engine | | | | | | | |
| N_LS | 4.5 | 138 | 82 | 157 | 0.1 | 4 | 161 |
| N_HS | 4.5 | 138 | 587 | 164 | 0.1 | 4 | 169 |

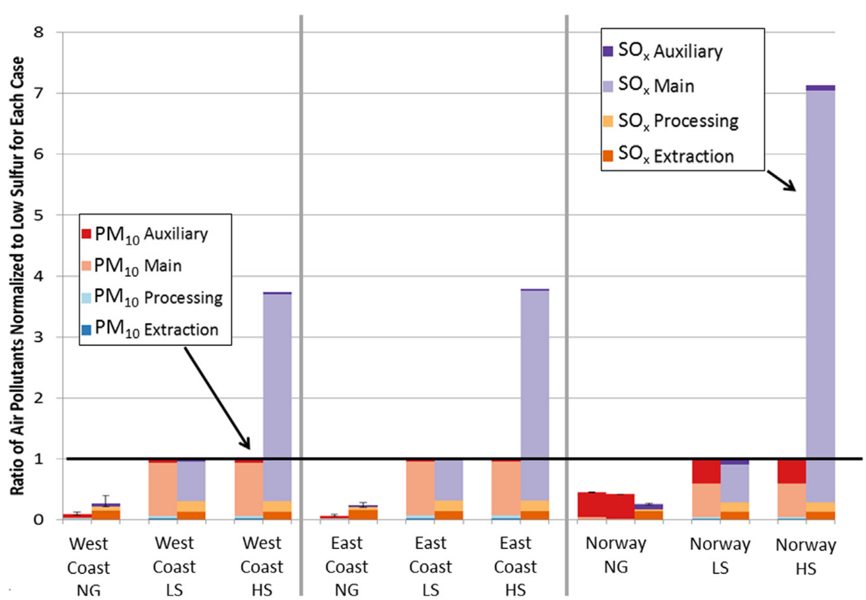
Note: the Pathway Code refers to the main engine fuel _main engine cycle (Spark-Ignited or Compression-Ignited) with the number indicating the fuel pathway for refueling (as referenced in Supporting material, Section A, Table A.1)
Note: GHGs represent the $GWP_{100}$ weighted combination of $CH_4$, $CO_2$, and $N_2O$; GREET and TEAMS multipliers (1 g $CO_2$=1 g $CO_2$e; 1 g $CH_4$=30 g $CO_2$e; and 1 g $N_2O$ =265 g $CO_2$e) are consistent with current (AR5) IPCC multipliers for 100-year equivalent per-mass warming potential compared to $CO_2$.

(e.g., 100 years out). When pulse GWP values are used, Tables 3–5 show that for most pathways, total GHGs are lower than the low-sulfur diesel pathway, though some LNG pathways do increase GHGs up to 12% (See supporting material, Figure C.3). This is especially true for the spark-ignited engine, where all pathways are worse than the low sulfur case. Although the bulk of the overall GHGs comes from $CO_2$ (supporting material, Figure C.5), in the LNG cases $CO_2$ emissions decrease; therefore, when there is a GHG penalty in the LNG comparison, it is attributed to the increase in $CH_4$ emissions (Supporting material, Fig. C.4).

While $CO_2$ emissions are slightly less for natural gas, $CH_4$ emissions are higher. Higher $CH_4$ emissions come from both upstream processes and main engine consumption, leading to two conclusions. First, $CH_4$ emissions for natural gas fuel are highly affected by the way the natural gas is obtained, the amount of time (e.g., distance) in the natural gas pipeline, and the amount of time in storage. Second, vessel operations are important – more efficient engines and engines that technologically control for pollutant formation produced fewer emissions.

We consider how uncertain GWP ratios for methane might affect the results of this analysis, which vary among the IPCC AR 4 (25) and AR5 (30 and 36), and differ when considering feedback. While this analysis uses a GWP of 30 (Myhre et al., 2013), which does not include feedback, we also solve for the GWP values that would achieve parity between GHGs from natural gas and from the LS petroleum pathway. In the cargo transport case studies (West Coast and East Coast), the GWP ratios range from 45 to 142, well above the debated values. The spark-ignited service vessel case values range from 18 to 33, right around the current estimates, while the compression-ignited values for the service vessel range from 36 to 134, comparable to the cargo transport vessel pathways, (see Supporting material, Table C.1). Brandt et al. (2014) suggest that the emissions rates used in GREET 2013 might underestimate actual emissions. Therefore, we conducted a sensitivity analysis by increasing the methane leakage rates by a factor of 1.75 for the West Coast case with the highest emissions. $CH_4$ emissions increased further after the leakage rates were adjusted (see Supporting material, Fig. C.4). Nevertheless, total GHG emissions were still less than the traditional fuel cases (see Supporting material, Fig. C.5).

However, if a vessel is converted to natural gas it will not make just one trip, but will use natural gas throughout its lifetime, and will likely be replaced with another natural gas vessel, as the infrastructure for refueling is already in place. Therefore we also



NOTE: Whiskers represent the range of results around the mathematical average of pathways in each case; they illustrate how various pathways would modify TFCA results for LNG upstream, in terms of overall results. See Appendix C for other emissions.

**Fig. 3.** Ratio of $PM_{10}$ and $SO_x$ Emissions for each set of fuel pathways, normalized to the low sulfur pathway in each case (NG=Natural Gas, LS=Low Sulfur Diesel, HS=High Sulfur Diesel, Main=Main Engines, Auxiliary=Auxiliary Engines).

report the fleet conversion TWP introduced by Alvarez et al. (2012). A value of TWP=1 indicates that the new technology (LNG) is climate neutral with the old technology (low- and high-sulfur diesel) at that particular point in time. Fig. 4 exhibits a GHG benefit right away in the best natural gas case for a transition from high-sulfur marine fuel (HS) to LNG, and most transition cases from low-sulfur marine fuel (LS) to LNG show a climate benefit within 30 years from conversion, though reaching climate parity will take longer (130–-190 years) for spark-ignited natural gas engines. The specific pathway chosen can also have a large effect on the time needed to reach climate parity, with variations of over 50 years (Supporting material, Fig. C.6). The gap between the LS and HS cases in the service vessel (Norway case) is different than the cargo transport vessel cases because the differences in $CO_2$ emissions among the service vessel cases is not as large (Supporting material, Fig. C.2), due to different operating conditions for a service tug/tow vessel and a cargo-carrying OGV (Table 2).

## 4. Discussion

### 4.1. TFCA emissions discussion

While net GHG penalties might inhibit policy endorsement of LNG, technology providers recognize opportunities for adoption. For example, engine technology providers report innovations in recent years that have reduced methane slip during combustion (Pakarinen, 2013; Rolls-Royce Marine, 2012). Using conventional wells and minimizing pipeline distance and storage time would reduce $CH_4$ emissions. In order to reduce long-run pipeline releases of $CH_4$ and minimize landside storage times for LNG distribution and bunkering, careful alignment with low-GHG upstream infrastructure is needed so that LNG not only produces less pollution but also minimizes net GHGs where initial adoption of LNG may be economically favored. Prioritizing replacing HS diesel before LS diesel will also achieve greater GHG benefits in a pulse context and sooner parity in a TWP context.

Pulse $GWP_{100}$ (as provided by GREET and TEAMS models) suggests a GHG benefit at the hundred-year mark for our WC and EC cases when a trip uses natural gas instead of liquid marine fuels for compression ignited engines. This result is highly dependent on the variations in the upstream processes as a component of overall emissions (Supporting material, Section C). Our results are consistent with other studies on $CH_4$ emissions from natural gas. For example, an analysis of cars in Switzerland found that natural gas pathways fell within the range of other fuel sources, including diesel, gasoline, and biogas (Yazdanie et al., 2014). Other studies have found that switching to natural gas does not improve GHG emissions, especially considering $CH_4$ leakage impacts on global warming potential (Brynolf et al., 2014a; Lowell et al., 2013; Meyer et al., 2011), though other studies, using updated emissions factors and leakage rates (Burnham et al., 2013), found that natural gas reduced the GHGs emitted (Bengtsson et al., 2011a; Bengtsson et al., 2014). These updated rates show that reducing both upstream and downstream $CH_4$ leakage may improve the pulse GWP performance of LNG as a marine fuel.

But GWP results at a given point in time provide a "weak" assessment of actual climate change impacts due to a fuel transition. Instead, TWP provides a more powerful assessment of these impacts by considering transition impacts over time. The TWP results for fleet conversion to LNG show that for compression-ignited engines a fuel transition will reach climate parity within 30 years, though the range of years needed to achieve climate neutrality can vary depending on the upstream pathway chosen (see Supporting material, Figure C.6). We also find that the time to achieve neutrality is higher for spark-ignited engines unless additional reductions in methane slip are developed for downstream engine operations. A widespread switch to natural gas that is climate neutral may require policy decisions that consider GHG-neutrality (designs or offsets) for marine and other applications. If achieving GHG parity or reduction were required conditions influencing where to employ LNG in marine systems, the TWP results can be interpreted as setting higher priority on LNG conversion from high-sulfur residual fuels where maximum reductions in air pollutants and earliest parity in GHGs would be jointly achieved.

### 4.2. Regional energy policy drivers for infrastructure investment and policy action

Our regional assessment of drivers identified in Europe and the

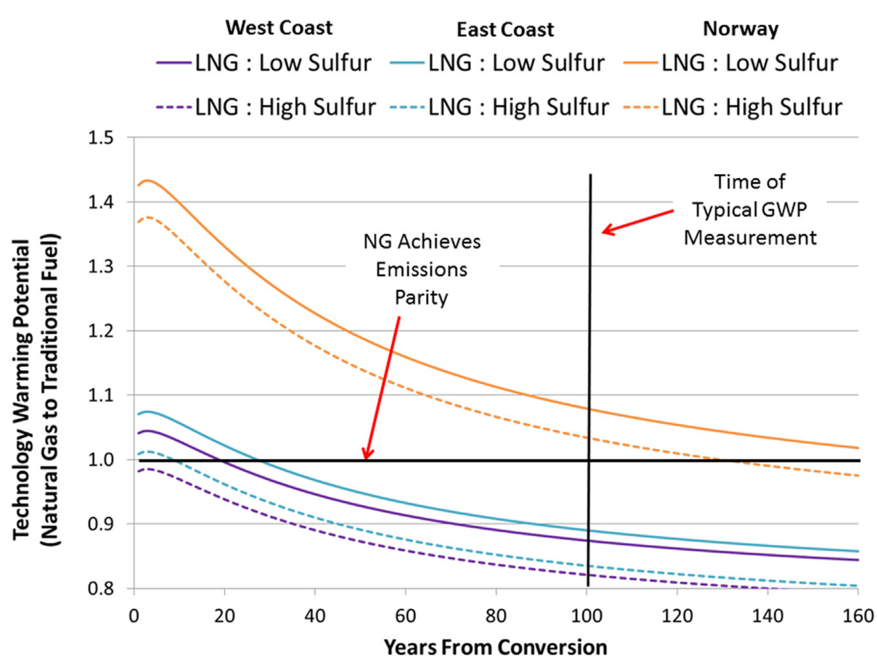



**Fig. 4.** Technology warming potential for natural gas as compared to traditional fuels for each case.

U.S. that may affect the introduction and rate of diffusion of LNG fuel into the maritime sector relies upon the nine IEA regions in the World Energy Balance (IEA, 2012):

1. Organisation for Economic Cooperation and Development (OECD) Americas;
2. OECD Europe;
3. Middle East;
4. Asia excluding China;
5. China;
6. OECD Asia Oceania;
7. non-OECD Europe and Eurasia;
8. non-OECD Americas; and
9. Africa.

Of these regions, we present most detailed results for the first six because these IEA regions also include the major world ports, according to the American Association of Port Authorities (2013). For example, we omit from our summary in Table 6 and Fig. 7 an assessment of non-OECD Americas and Africa. However, all regions are included in our global IEA data for export/import, price, and consumption trends (see Fig. 6 and Supporting material, Section D).

### 4.2.1. Environmental: regulation of air emissions

As described in Section 1.2, the policy record for **OECD America** and **OECD Europe** reflects leading action to control ship emissions, both through international agreements to designate special areas under MARPOL Annex VI, and in U.S. regulation and European Commission directives. In **China**, the Legislative Council of Hong Kong has signaled emerging air quality standards for ships at dock (Government of Hong Kong, 2015), catalyzed by the industry's voluntary Fair Winds Charter (Hong Kong Civic Exchange, 2014). The other regions have limited regulatory action, although voluntary and advocacy efforts to reduce ship emissions exist locally in **Asia excluding China** and **OECD Asia Oceania**.

### 4.2.2. Social: policies involving alternative energy and GHGs

Support for LNG may be inhibited in regions with stronger directives on GHG mitigation targets, especially where near-term warming reductions are important. These conditions appear to be most relevant in **OECD Europe**, where European Union (EU) directives may result in low-GHG criteria for alternative fuels performance; similarly, parts of **OECD America,** such as California, may set regional commitments that require GHG reductions in the transport sector, including marine vessels. Australia, part of **OECD Asia Oceania,** repealed their Clean Energy Act in 2014, and we identified no significant activity in other IEA regions to impose GHG criteria on LNG in marine transportation applications.

### 4.2.3. Fuel infrastructure/engine technology

Our assessment also considered areas where increases in maritime demand could already be necessitating investment in fueling infrastructure, potentially including natural gas capacity. We evaluated increases in cargo throughput in top-ranked regional ports. Fig. 7 shows the top 100 global ports by 2012 TEUs along with the Compound Annual Growth Rate (CAGR) for the years 2002–2012 for the ports that remained on the top 100 list for both years, sorted by region. It shows that major ports are increasing in throughput during that time. Major port regions include **OECD Americas**, **OECD Europe**, the **Middle East**, **Asia excluding China**, **China**, and **OECD Asia Oceania**. Of these, **OECD Americas**, **OECD Europe**, and the **Middle East** are regions of high maritime demand where natural gas consumption is also substantial (and, for the Middle East, increasing rapidly).

### 4.2.4. Economic: price of fuels

While global natural gas prices have been rising over the last decade, natural gas fuel is still competitive with current liquid petroleum marine fuels (Fig. 5). Moreover, a review of IEA regional pricing trends indicates that LNG price varies among world regions (see Supporting material, Section D, Table D.1). In many regions, the global LNG price trend is replicated, with a notable exception in **OECD Americas**, where increased natural gas production in North America is associated with declining prices since 2004; prices in **OECD America** are less than half the world natural gas price in recent years (see Supporting material, Section D). Generally, where regional natural gas prices are less than world average price (e.g., **non-OECD Europe and Eurasia** and **Asia excluding China**), IEA data show these regions to be net exporters of natural gas energy. These regions where apparent domestic supply exceeds apparent regional demand may be price sensitive, which could provide opportunity for maritime investment in LNG fuel transition.

**OECD Europe** natural gas pricing trends most closely match the world average natural gas pricing, perhaps consistent with Europe's history as a net importer of natural gas from other IEA regions. **China** and the **Middle East** consumed less than one-quarter the natural gas consumed in **OECD America** prior to 2005; moreover, the IEA has not begun reporting natural gas pricing statistics for these regions. However, as discussed in Section 4.2.1, these regions exhibit the highest overall growth in port cargo

**Table 6**
Summary of main drivers favoring or inhibiting marine transportation transition to LNG fuel.

| Region | Driver | | | | |
|---|---|---|---|---|---|
| | Environmental[a] Emissions control regulation | Social (climate)[b] GHG policy activity | Infrastructure/technology[c] Domestic natural gas consumption | Economic price[d] Natural gas price | Maritime demand[e] Growth in major port activity |
| **OECD America** | Favors | May inhibit | Favors | Favors | May favor |
| **OECD Europe** | Favors | Inhibits | Favors | Inhibits | May favor |
| **Middle East** | Inhibits | Favors | May favor | Inhibits | Favors |
| **China** | May favor | Favors | May favor | Inhibits | Favors |
| **Asia excluding China** | Inhibits | Favors | May favor | May favor | May favor |
| **OECD Asia Oceania** | Inhibits | Favors | Inhibits | Inhibits | May favor |

Notes: A detailed version of this table is in Supporting material, Section D, Table D.1, including a narrative for each driver and region.

[a] Stricter emissions control regulation, especially addressing regional shipping, favors cleaner fuels like LNG in marine transportation.

[b] More active GHG policy activity, including regional GHG commitments, inhibits fuels that are not climate neutral, like LNG in a technology warming potential context.

[c] Developed fuel infrastructure across the fuel cycle, and vessel/engine technology design capacity favors fuel transition to LNG in marine transportation.

[d] Long-run price competitiveness and regional price advantages for alternative fuels favors fuel transition investment strategies, like LNG in marine transportation.

[e] Rapidly growing demand for goods movement through major regional ports is associated with cargo transport and service vessels energy growth for marine fuels.

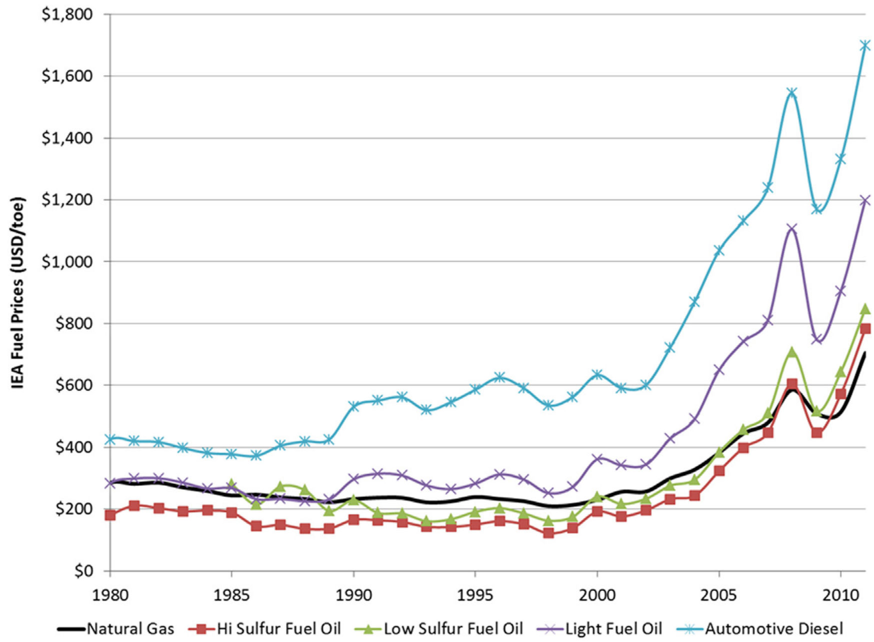



**Fig. 5.** Global historical fuel prices by fuel type.

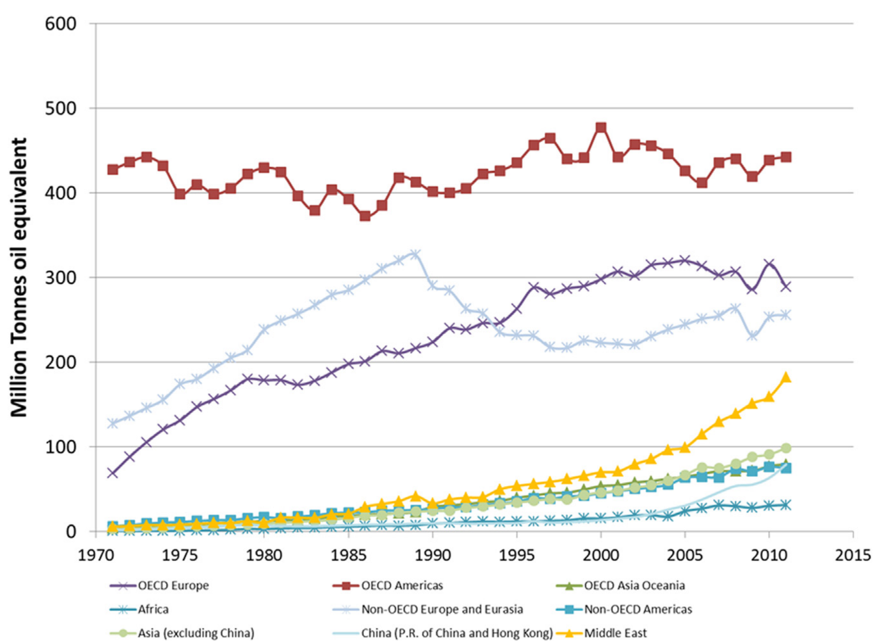



**Fig. 6.** Final consumption trends for natural gas, all sectors, by region.

volumes (Fig. 7 for containerized TEUs).

**Asia excluding China** is a region with major ports that indicates strong price-trend parity with the world average natural gas price, especially in the last few years. Unlike Europe, however, this region has been a net exporter of natural gas since the 1980s (Supporting material, Table D.1), even while its in-region consumption has increased steadily (Fig. 6).

#### 4.2.5. *Demand for maritime transport*

Natural gas consumption has been increasing globally over the past 40 years (Fig. 6), in some regions faster than in others (IEA, 2012). Increased consumption should be associated with more developed natural gas infrastructure, and experience with natural gas technologies make transitioning to natural gas in the marine sector easier. As shown in Fig. 6, **OECD Americas** has consumed more natural gas than other regions, including the transport sector, lowering potential risk for new adopters in the marine sector.

**OECD Europe** and **non-OECD Europe and Eurasia** also have multi-decadal trends of significant natural gas consumption. For **Europe**, this experience includes marine vessel applications, as there are currently many vessels in the fleet using only natural gas for propulsion (Acciaro, 2014; Æsoy et al., 2011; Motor Ship, 2013). Moreover, European designers of marine engines are leading development of natural gas marine power technologies (Rolls-Royce, 2014; Wärtsilä, 2014), including many vessels that are designed to be dual-fuel.

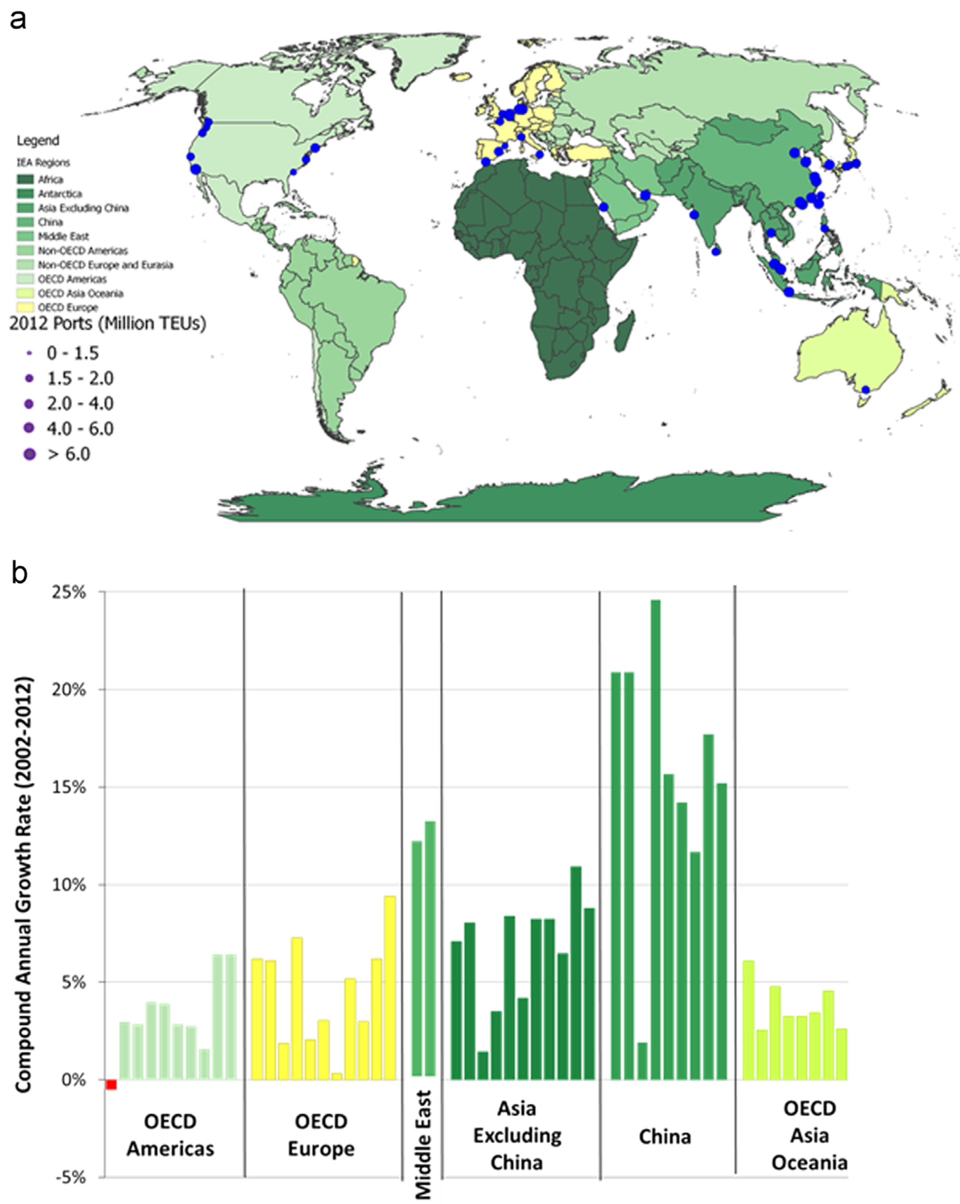



**Fig. 7.** Major ports of the world: (a) mapped by TEU volume; and (b) growth rates 2002-2012 (CAGR) by region.

Interestingly, the **Middle East** demonstrates a decadal trend of rapidly increasing both in-region consumption (Fig. 6) and export volumes (Supporting material, Table D.1), though IEA pricing data do not report natural gas information for the region. This region may exhibit a rapidly changing energy portfolio that includes natural gas; given the important role maritime transport plays in delivering upstream energy extraction to upstream processing, the **Middle East** may be an emerging opportunity for LNG maritime fuel consideration.

*4.2.6. Global assessment summary*

A summary of this initial assessment is presented in Table 6, with some annotated detail in Supporting material, Table D.1. On balance, this qualitative assessment suggests that **OECD America** and **OECD Europe** appear most ready to take advantage of a switch to natural gas. A more mature natural gas infrastructure is suggested by the long history of natural gas consumption. Both regions have strong environmental records, including air emission regulations for shipping. For **OECD America**, low pricing and transport sector experience also suggests potential catalysts for natural gas technology diffusion. For **OECD Europe**, marine engine design innovation capacity and diverse shipping markets in oceangoing, inland waterway, and shortsea shipping markets offer multiple points of entry into both larger and smaller marine vessels. Moreover, in-region conditions such as North Sea ports can offer Europe offshore natural gas supply and domestic maritime energy demand, where ports near natural gas terminals could take advantage of the lower prices and proximity to natural gas supply and use LNG in their service vessels.

The regions of **China** and **Asia excluding China** may offer opportunities for natural gas transition to maritime transport for different reasons. These regions are currently leaders in shipbuilding for the new century fleets; in particular, China, the Republic of Korea, and Japan together built over 90% of new gross tonnage in the world (Stopford, 2012; UNCTAD, 2013). Natural gas vessel and propulsion designs will be constructed in these regions' shipyards. Chinese and other Asian ports have led growth in demand for marine transport of cargoes, especially containerized cargoes for decades. Energy rich regions like the **Middle East** also have potential due to their rapidly growing port volumes, and synergy with upstream transport of energy products including natural gas. However, a limiting factor for these three regions may depend upon how rapidly natural gas infrastructure develops near maritime centers of activity.

## 5. Conclusions and policy implications

LNG fuels offer significant local pollution emissions advantages in the marine transport sector over traditional marine petroleum fuels. Natural gas in marine transportation applications will reduce important criteria air pollutants (e.g., $SO_x$, and $PM_{10}$) substantially below all current and proposed emissions standards for traditionally fueled marine diesel engines and does not increase $NO_x$ emissions. Reductions in air emissions are greater when natural gas is compared with high-sulfur fuels, especially for $SO_x$ and $PM_{10}$. A switch to natural gas will achieve these reductions immediately and persist over the life of the gas-fueled marine engine technology.

Total fuel-cycle comparisons with traditional marine fuels based on “pulse” emissions show that LNG can reduce net GHGs in marine transportation. However, this requires energy policy attention to lessen the impact of $CH_4$ leakage on $GWP_{100}$ through better upstream infrastructure designs, continued downstream innovation to minimize engine combustion methane slip, or a combination of the two. Moreover, this is dependent upon the GWP ratio chosen. Depending on leakage in the upstream pathways, $GWP_{100}$ net GHGs using natural gas are less than the net GHGs from ECA-compliant marine petroleum fuels, though the service-vessel case using spark-ignited engines did not outperform traditional petroleum fuels. Upstream pathway $CH_4$ leakage can be reduced through improved technology and/or operating practices at production sites, shorter pipeline distances from extraction to processing, reducing leakage in pipelines, better recovery of pipeline fugitive $CH_4$ losses, shorter LNG storage times, better recovery of LNG boil off, or any combination of the above.

Considering the technology transition from petroleum to LNG marine vessels, the TWP shows that natural gas as a marine fuel achieves climate parity within 30 years for diesel ignited engines, though could take up to 190 years to reach climate parity with conventional fuels in a spark ignited engine without additional energy policy and technology intervention. Fleet conversion to natural gas acknowledges that natural gas substitution persists over a vessel's operating life and across fleet replacement cycles. Therefore, a technology transition to natural gas marine technology is not immediately climate neutral without continued requirements for substantial improvements in both upstream and downstream $CH_4$ leakage control. Moreover, prioritizing HS transition to LNG can achieve GHG parity soonest in either GWP or TWP contexts.

Marine transport adoption of LNG fuels will depend on multiple drivers important to energy policy. Policy drivers include environmental goals to reduce or control traditional air emissions, policies related to low-GHG performance of alternative energy, and infrastructure development decisions that offer LNG energy access to the marine sector. Technology drivers include engine design innovations to reduce methane slip during combustion and shipbuilding that accommodates naval architecture requirements matching onboard LNG fuel storage and propulsion with an emerging LNG bunkering sector. Economic drivers such as the relative price advantage and the expected demand for new technology, both of which vary regionally, also affect how quickly natural gas fuels may be adopted by marine transport.

**OECD America** and **OECD Europe** demonstrate a consistent set of drivers favoring adoption of natural gas technology in marine transportation. For shortsea, regional oceangoing, or service-vessel cases considered here, a transition to natural gas in marine transportation is likely to be justified on both economic and air quality dimensions, at least in local port areas and regions where ships contribute to air quality degradation. LNG in service vessels can be fully implemented within a given policy jurisdiction, and our results suggest that LNG may be a competitive alternative to cleaner fuels or aftertreatment technology. Existing infrastructure and technology capacity in North America and Europe provide marine transportation with onboard technologies and access to natural gas bunkering. Natural gas can meet or exceed environmental standards economically if the observed price differences between gas and petroleum persist. Offsets for increased GHGs may need to be considered to support a technology transition to natural gas, mainly in consideration of the TWP results reported here.

A full-scale conversion to LNG in marine transportation is less likely in the near term given better niche matches, such as: (a) the better fit of LNG fuel to shorter transport routes that enable frequent fueling (technology limit); (b) impractical long-term development of necessary LNG supply and delivery to ships (infrastructure limit); and (c) multi-decade (up to 190 years) time before achieving fleetwide climate-neutral performance of LNG in marine transportation (technology warming potential limit).

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## Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2015.08.027.

## References

AAPA, 2013. Port Industry Statistics. American Association of Port Authorities, Available at: ⟨http://www.aapa-ports.org/Industry/content.cfm?ItemNumber=900#Statistics⟩ (accessed 29.03.15).
Acciaro, M., 2014. Real option analysis for environmental compliance: LNG and emission control areas. Transp. Res. Part D: Transp. Environ. 28, 41–50.
Adom, F., Dunn, J.B., Elgowainy, A., Han, J., Wang, M., 2013. Life Cycle Analysis of Conventional and Alternative Marine Fuels in GREET. Energy Systems Devision. Argonne National Laboratory, Argonne, IL, p. 58 (accessed December 2014) https://greet.es.anl.gov/publication-marine-fuels-13.
Æsoy, V., Magne Einang, P., Stenersen, D., Hennie, E., 2011. LNG-Fuelled Engines and Fuel Systems for Medium-Speed Engines in Maritime Applications. 2011-01-1998, SAE Technical Paper, Available at: ⟨http://papers.sae.org/2011-01-1998/⟩ (accessed December 2014). doi:10.4271/2011-01-1998.
Alvarez, R.A., Pacala, S.W., Winebrake, J.J., Chameides, W.L., Hamburg, S.P., 2012. Greater focus needed on methane leakage from natural gas infrastructure. Proc. Natl. Acad. Sci. USA 109 (17), 6435–6440.
ANL, 2014. The GREET Model. Argonne National Laboratory, Argonne, IL (accessed May 2015)https://greet.es.anl.gov/.
Arteconi, A., Brandoni, C., Evangelista, D., Polonara, F., 2010. Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe. Appl. Energy 87 (6), 2005–2013.
Bazari, Z., Longva, T., 2011. Assessment of IMO mandated energy efficiency measures for international shipping. Estimated $CO_2$ Emissions Reduction from Introduction of Mandatory Technical and Operational Energy Efficiency Measures for Ships. Project Final Report, 31. Lloyd's Register and Det Norske Veritas. International Maritime Organization document MEPC 63/INF.2. London, UK, 62.
Bengtsson, S.K., Fridell, E., Andersson, K.E., 2014. Fuels for short sea shipping: a comparative assessment with focus on environmental impact. Proc. Inst. Mech. Eng. Part M: J. Eng. Marit. Environ. 228 (1), 44–54.
Bengtsson, S., Andersson, K., Fridell, E., 2011a. A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels. Proc. Inst.

Mech. Eng. Part M: J. Eng. Marit. Environ. 225 (2), 97–110.
Bengtsson, S., Andersson, K., Fridell, E., 2011b. Life Cycle Assessment of Marine Fuels – A Comparative Study of Four Fossil Fuels for Marine Propulsion. Chalmers University of Technology, Gothenburg, Sweden (Technical report No. 11:125).
Boucher, O., Reddy, M.S., 2008. Climate trade-off between black carbon and carbon dioxide emissions. Energy Policy 36 (1), 193–200.
Brandt, A.R., et al., 2014. Energy and environment. Methane leaks from North American natural gas systems. Science 343 (6172), 733–735.
Brinkman, N., Wang, M., Weber, T., Darlington, T., 2005. Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems: A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions. Argonne National Laboratory, Argonne, IL, p. 238 (accessed December 2014)http://www.transportation.anl.gov/pdfs/TA/339.pdf.
Brynolf, S., Magnusson, M., Fridell, E., Andersson, K., 2014a. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transp. Res. Part D: Transp. Environ., 6–18.
Brynolf, S., Fridell, E., Andersson, K., 2014b. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod., 7486–7495.
Burnham, A., Han, J., Elgowainy, A., Wang, M., 2013. Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET Model. Argonne National Laboratory, Argonne, IL (accessed 20.12.14)https://greet.es.anl.gov/publication-ch4-updates-13.
Camuzeaux, J.R., Alvarez, R.A., Brooks, S.A., Browne, J.B., Sterner, T., 2015. Influence of Methane Emissions and Vehicle Efficiency on the Climate Implications of Heavy-Duty Natural Gas Trucks. Environ. Sci. Technol.
Capaldo, K., Corbett, J.J., Kasibhatla, P., Fischbeck, P., Pandis, S.N., 1999. Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean. Nature 400 (6746), 743–746.
Choi, W., Song, H., 2014. Well-to-wheel analysis on greenhouse gas emission and energy use with natural gas in Korea. Int. J. Life Cycle Assess., 1–11.
Corbett, J.J., Thomson, H., Winebrake, J.J., 2014. Natural Gas for Waterborne Freight Transport: A Life Cycle Emissions Assessment with Case Studies. U.S. DOT Maritime Administration, Washington, DC http://www.marad.dot.gov/documents/Total_Fuel_Cycle_Analysis_for_LNG.pdf.
Corbett, J.J., Fischbeck, P., 1997. Emissions from ships. Science 278 (5339), 823–824.
Corbett, J.J., Winebrake, J., 2008a. Total Fuel Cycle Analysis for Alternative Marine Fuels: Sulfur and CO2 Emissions Tradeoffs of California's Proposed Low-Sulfur Marine Fuel Rule. Energy and Environmental Research Associates, LLC, Pittsford, NY http://www.arb.ca.gov/regact/2008/fuelogv08/apphfuel.pdf.
Corbett, J.J., Winebrake, J.J., 2008b. Emissions tradeoffs among alternative marine fuels: Total fuel cycle analysis of residual oil, marine gas oil, and marine diesel oil. J. Air Waste Manag. Assoc. 58 (4), 538–542.
Danish Maritime Authority, 2012. North European LNG Infrastructure Project: A feasibility study for an LNG filling station infrastructure and test of recommendations. Final Report. Available at: ⟨http://www.dma.dk/themes/LNGinfrastructureproject/Documents/Final%20Report/LNG_Full_report_Mgg_2012_04_02_1.pdf⟩. (accessed 31.03.15).
DeLuchi, M.A., 1991. Emissions of greenhouse gases from the use of transportation fuels and electricity. Argonne National Lab, Argonne, IL http://www.osti.gov/scitech/servlets/purl/5457338.
Drydocks World, 2014. Drydocks World and Dubai Maritime City to build world's first LNG-powered harbor tug "Elemarateyah". Drydocks World, United Arab Emirates (accessed 29.03.15)http://www.drydocks.gov.ae/en/news/green.tug.aspx.
Elgowainy, A., Burnham, A., Wang, M., Molburg, J., Rousseau, A., 2009. Well-to-wheels energy use and greenhouse gas emissions of plug-in hybrid electric vehicles. SAE Int. J. Fuels Lubr. 2 (1), 627–644.
European Commission, 2013. Communication From the Commission to the European Parliament. The Council. The European Economic and Social Committee and the Committee of the Regions Clean Power for Transport: A European Alternative Fuels Strategy. COM/2013/017 Final (24.01.13).
European Commission Maritime, 2015. European Commissions' study on LNG as a shipping fuel shows industry's support. European Commission Mobility and Transport (accessed 29.03.15).
European Parliament, 2014. Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure Text with EEA relevance, OJ L, 307, 28.10.2014, pp. 1–20 (accessed 29.03.15).
European Parliament, 2012. Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels, (OJ L), 327, 27.11.12, pp. 1–13. Official Journal of the European Union: Legislation ed.
Farrell, A.E., Keith, D.W., Corbett, J.J., 2003. A strategy for introducing hydrogen into transportation. Energy Policy 31 (13), 1357–1367.
Farrell, A.E., Sperling, D., 2007. A low-carbon fuel standard for California, Part 1: Technical analysis. Institute of Transportation Studies, UCD-ITS-RR-07-07. Institute for Transportation Studies: University of California, Davis, Davis, CA (accessed December 2014).
Fullenbaum, R., Fallon, J., Flanagan, B., 2013. Oil & Natural Gas Transportation & Storage Infrastructure: Status, Trends, & Economic Benefits. IHS Global Inc for American Petroleum Institute, Washington, DC, http://www.api.org/~/media/Files/Policy/SOAE-2014/API-Infrastructure-Investment-Study.pdf.
Lloyd, Germanischer, 2011. Costs and Benefits of LNG as Ship Fuel for Container Vessels: Key results from a GL and MAN joint study. Germanischer Lloyd, Germany (accessed December 2014).
Government of Hong Kong, 2015. New regulation to require ocean-going vessels to switch to clean fuel while at berth. Available at: ⟨http://www.info.gov.hk/gia/general/201503/11/P201503110549.htm⟩ (accessed 29.03.15).
Håberg, S.H., 2003. LNG Study Tour: 'Insights into a new market'. Rolls Royce International Presentation, London, UK.
Han, J., Forman, G.S., Elgowainy, A., Cai, H., Wang, M., DiVita, V.B., 2015. A comparative assessment of resource efficiency in petroleum refining. Fuel 157, 292–298.
Hassellöv, I., Turner, D.R., Lauer, A., Corbett, J.J., 2013. Shipping contributes to ocean acidification. Geophys. Res. Lett. 40 (11), 2731–2736.
Holden, D., 2014. Liquefied Natural Gas (LNG) Bunkering Study. PP087423-4, U.S. DOT Maritime Administration, Available at: ⟨http://trid.trb.org/view.aspx?id=1323288⟩ (accessed 29.03.15).
Hong Kong Civic Exchange, 2014. Fair Winds Charter. Hong Kong Civic Exchange, Available at: ⟨http://civic-exchange.org/materials/theme/files/FWC.html⟩ (accessed 29.03.15).
Howarth, R.W., Santoro, R., Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim. Change 106 (4), 679–690.
Huo, H., Wang, M., Bloyd, C., Putsche, V., 2008. Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. 43. Environ. Sci. Technol., pp. 750–756.
Huo, H., Wu, Y., Wang, M., 2009. Total versus urban: well-to-wheels assessment of criteria pollutant emissions from various vehicle/fuel systems. Atmos. Environ. 43 (10), 1796–1804.
IEA. 2015. Norway: Electricity and heat for 2012. Retrieved from: ⟨http://www.iea.org/statistics/statisticssearch/report/?country=NORWAY&product=electricityandheat&year=2012⟩ (accessed July 2015).
IEA, 2012. Energy Prices and Taxes. International Energy Agency, ESDS International, University of Manchester, Paris, France, http://dx.doi.org/10.5257/iea/ept/2012q1.
IMO, 2014a. Nitrogen Oxides (NOx) – Regulation 13. International Maritime Organization, London, UK (accessed December 2014)..
IMO, 2014b. Third IMO GHG Study 2014. International Maritime Organization (IMO), London, UK (accessed 05.04.15).
IMO, 2013. Prevention of Air Pollution from Ships. International Maritime Organization, London, UK.
Jayaram, V., Khan, M.M.Y., Miller, J.W., Welch, M.W.A., Johnson, K., Cocker, D.R., 2010. Evaluating Emission Benefits of a Hybrid Tug Boat. Contract # 07-413 and #07-419. California Air Resources Board, Sacramento, CA (accessed December 2014).
Jorgensen, R., 2011. Slow Steaming: The Full Story. A.P. Moller-Maersk Group, Copenhagen, Denmark https://www.yumpu.com/en/document/view/7803715/slow-steaming-the-full-story-maersk.
Korakianitis, T., Namasivayam, A., Crookes, R., 2011. Natural-gas fueled spark-ignition (SI) and compression–ignition (CI) engine performance and emissions. Prog. Energy Combust. Sci. 37 (1), 89–112.
Kunz, P., Gorse, P., 2013. Development of High-Speed Engines for Natural Gas Operation in Tugs. Tugnology '13, London, UK.
Lauer, A., Eyring, V., Corbett, J.J., Wang, C., Winebrake, J.J., 2009. Assessment of near-future policy instruments for oceangoing shipping: impact on atmospheric aerosol burdens and the earth's radiation budget. Environ. Sci. Technol. 43 (15), 5592–5598.
Lawrence, M.G., Crutzen, P.J., 1999. Influence of NOx emissions from ships on tropospheric photochemistry and climate. Nature 402 (6758), 167–170.
Lowell, D., Wang, H., Lutsey, N., 2013. Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping. The International Council on Clean Transportation, Washington, DC (accessed December 2014).
Manne, A.S., Richels, R.G., Weyant, J.P., 1979. Energy policy modeling: a survey. Oper. Res. 27 (1), 1–36.
MarineLink, 2013. First US Big Ship LNG Bunkering Terminal Proposed. MarineLink, Available at: ⟨http://www.marinelink.com/news/bunkering-terminal360363.aspx⟩ (accessed 01.01.13).
Maring, G., Mintz, M., 2014. The rapidly improving US energy outlook: positive implications for transportation. TR News 292, 3.
Meyer, J., Stahlbock, R., Voß, S., 2012. Slow steaming in container shipping, In: Proceedings of the 2012 45th Hawaii International Conference on System Sciences. IEEE, pp. 1306–1314.
Meyer, P.E., Green, E.H., Corbett, J.J., Mas, C., Winebrake, J.J., 2011. Total fuel-cycle analysis of heavy-duty vehicles using biofuels and natural gas-based alternative fuels. J. Air Waste Manag. Assoc. 61 (3), 285–294.
Milliken, J., Joseck, F., Wang, M., Yuzugullu, E., 2007. The advanced energy initiative. J. Power Sources 172 (1), 121–131.
Motor Ship, T., 2013. The first tugs with pure gas propulsion. The Motor Ship. Available at: ⟨http://www.motorship.com/news101/ships-and-shipyards/the-first-tugs-with-pure-gas-propulsion⟩ (accessed December 2014).
Moura, M.C.P., Branco, D.A.C., Peters, G.P., Szklo, A.S., Schaeffer, R., 2013. How the choice of multi-gas equivalency metrics affects mitigation options: the case of $CO_2$ capture in a Brazilian coal-fired power plant. Energy Policy 61 (0), 1357–1366.
Myhre, G., et al., 2013. Anthropogenic and natural radiative forcing. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 659–740.
NREL, 2013. Life Cycle Greenhouse Gas Emissions from Electricity Generation. NREL/FS-6A20-57187. National Renewable Energy Laboratory, Golden, CO

(accessed December 2014)http://www.nrel.gov/docs/fy13osti/57187.pdf.
Pakarinen, R., 2013. Twice as Good: Dual Fuel Two-Stroke. Twentyfour7magazine, 38–42.
Posplech, P., 2013. Full Speed Ahead with Gas. Marine News, 72.
Rolls Royce, 2013. Bergen Tankers selects Rolls-Royce Engines for LNG Conversion Project. Available at: ⟨http://www.rolls-royce.com/news/press_releases/2013/04062013_conversion_project.jsp⟩ (accessed 25.01.14).
Rolls-Royce, 2014. Bergen_C-gas engine. Rolls-Royce, Available at: ⟨http://www.rolls-royce.com/energy/energy_products/gas_engines/#Bergen_C-gas⟩ (accessed 10.03.14).
Rolls-Royce Marine, 2012. Overcoming Methane Slip, Rolls Royce Marine Builds Spark-Ignited LNG-Powered Engines. gCaptain. Available at: ⟨http://gcaptain.com/overcoming-methane-slip-rolls/⟩ (accessed 16.11.14).
Schlamadinger, B., Marland, G., 1996. Full fuel cycle carbon balances of bioenergy and forestry options. Energy Convers. Manag. 37 (6), 813–818.
Shen, W., Han, W., Chock, D., Chai, Q., Zhang, A., 2012. Well-to-wheels life-cycle analysis of alternative fuels and vehicle technologies in China. Energy Policy, 49296–49307.
Shine, K.P., 2009. The global warming potential – the need for an interdisciplinary retrial. Clim. Change 96 (4), 467–472.
Shine, K.P., Fuglestvedt, J.S., Hailemariam, K., Stuber, N., 2005. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Clim. Change 68 (3), 281–302.
Stopford, M., 2012. World Shipbuilding. In: Proceedings of the SMM Advance Press Conference 2012. Clarkson Research Services, Ltd., May 23.
TIAX LLC, 2007a. Full Fuel Cycle Assessment: Well to Tank Energy Inputs, Emissions, and Water Impacts. CEC-600-2007-002-D, California Energy Commission. Available at: ⟨http://www.energy.ca.gov/2007publications/CEC-600-2007-002/CEC-600-2007-002-D.PDF⟩ (accessed December 2014).
TIAX LLC, 2007b. Full Fuel Cycle Assessment: Well-To-Wheels Energy Inputs, Emissions, and Water Impacts. CEC-600-2007-004-F, California Energy Comission. Available at: ⟨http://www.energy.ca.gov/2007publications/CEC-600-2007-004/CEC-600-2007-004-F.PDF⟩ (accessed December 2014).
UNCTAD, 2013. Review of Maritime Transport 2013. E. 13.II.D.9. United Nations Conference on Trade and Development. Available at: ⟨http://unctad.org/en/publicationslibrary/rmt2013_en.pdf⟩ (accessed December 2014).
Wang, M., 2002. Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts. J. Power Sources 112 (1), 307–321.
Wang, M., Wu, M., Huo, H., Liu, J., 2008. Life-cycle energy use and greenhouse gas emission implications of Brazilian sugarcane ethanol simulated with the GREET model. Int. Sugar J. 110 (1317), 527–545.
Wärtsilä, 2014. Wärtsilä Gas-fired Engines. Wartsila. Available at: ⟨http://www.wartsila.com/en/power-plants/technology/combustion-engines/gas-engines⟩ (accessed 10.03.14).
Wärtsilä, 2012. Wärtsilä 2-Stroke Dual-Fuel: A Single Solution. Wärtsilä, Available at: ⟨http://www.wartsila.com/en/wartsila-2-stroke-dual-fuel-a-single-solution⟩.
Winebrake, J.J., Corbett, J.J., Meyer, P.E., 2007. Energy use and emissions from marine vessels: a total fuel life cycle approach. J. Air Waste Manag. Assoc. 57 (1), 102–110.
Winebrake, J.J., Corbett, J.J., Meyer, P.E., 2006. Total Fuel-Cycle Emissions for Marine Vessels: A Well-to-Hull Analysis with Case Study, In: Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, LCE2006, pp. 125–129.
Winebrake, J.J., Wang, M.Q., He, D., 2001. Toxic emissions from mobile sources: a total fuel-cycle analysis for conventional and alternative fuel vehicles. J. Air Waste Manag. Assoc. 51 (7), 1073–1086.
Winebrake, J., Corbett, J., Green, E., Lauer, A., Eyring, V., 2009. Mitigating the health impacts of pollution from oceangoing shipping: an assessment of low-sulfur fuel mandates. Environ. Sci. Technol. 43 (13), 4776–4782.
Wu, Y., Wang, M.Q., Sharer, P.B., Rousseau, A., 2006. Well-to-wheels results of energy use, greenhouse gas emissions and criteria air pollutant emissions of selected vehicle/fuel systems. Journal of Engines, SAE, 2006-01-0377. SAE Technical Paper. Available at: ⟨http://www.autonomie.net/docs/6%20-%20Papers/WTW/wtw_selected_vehicle_fuels_systems.pdf⟩. (accessed December 2014).
Yazdanie, M., Noembrini, F., Dossetto, L., Boulouchos, K., 2014. A comparative analysis of well-to-wheel primary energy demand and greenhouse gas emissions for the operation of alternative and conventional vehicles in Switzerland, considering various energy carrier production pathways. J. Power Sources, 249333–249348.